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FUEL PROPERTY EFFECTS ON THE UNAIDED COLD STARTING OF A TWO-CYCLE DIESEL ENGINE

INTERIM REPORT
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By

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In this program, a Detroit Diesel 4-53T was heavily insulated and cooled using a chilled coolant circulation system and cooled combustion air was provided. An external cranking motor was used to turn the engine at a constant rpm. Twenty-one test fuels were blended, and a minimum unaided starting temperature was obtained for each fuel. Multiple linear regression analysis was then performed in order to relate fuel properties to minimum starting temperature. Fuel properties examined were: viscosity, ASTM D 86 and D 2887 boiling point temperatures, cetane number, autoignition temperature, and flash point. Cetane number, viscosity, 50% boiling temperature, and autoignition temperature had statistically significant impact on minimum starting temperature. Keywords:

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SUMMARY

The effects of fuel properties on unaided cold startability were evaluated using a Detroit Diesel 4-53T engine. The engine was insulated with approximately 3 inches of fiberglass insulation and a chilled coolant was circulated through its cooling passages. An external cranking motor was used to turn the engine at a constant 150 revolutions per minute (rpm). Cold intake air was provided by using a vortex tube (Hilsch tube cold air generator). Then 21 test fuels were blended and run in the engine. The minimum starting temperature for each fuel was determined by successively cooling the engine and attempting a start at a particular temperature. The minimum starting temperature was the average of two "no-start" temperatures and two "start" temperatures that were no more than 2°C apart. A "no-start" condition was defined as a failure to attain a self-sustaining running state after 1 minute of cranking at 150 rpm. Analysis of fuel properties and minimum starting temperatures using a statistical analysis program yielded a stable minimum starting temperature prediction equation with cetane number, autoignition temperature, viscosity, and ASTM D 2887 50 percent off temperature as statistically significant independent variables at the 10-percent level of significance. The prediction equation for MUST using the D 2887 boiling temperature is:

$$\text{MUST} = 32.5445 + 8.6660 * \text{VISCOSITY} - 0.1423 * 50\%\ \text{BOILING POINT} - 0.6968 * \text{CETANE} + 0.0541 * \text{AUTOIGNITION TEMP}$$

where Minimum Unaided Starting Temperature (MUST) is in °C, 50 percent boiling point is ASTM D 2887 50 percent off temperature in °C, viscosity is ASTM D 445 kinematic viscosity at 40°C in centistokes, and autoignition temperature is ASTM E 659 in °C. Fuels that experienced fuel delivery (i.e., flow) problems or would not start at room temperature were not included in the analyses.

FOREWORD

This work was conducted at the Belvoir Fuels and Lubricants Research Facility (SwRI) located at Southwest Research Institute (SwRI), San Antonio, TX, under Contract Nos. DAAK70-82-C-0001 and DAAK70-85-C-0007 during the period January 1981 through December 1984. The work was funded by the U.S. Army Belvoir Research and Development Center, Ft. Belvoir, VA, with Mr. F.W. Schaekel (STRBE-VF) as the contracting officer's representative and Mr. M.E. LePera, Chief of Fuels and Lubricants Division (STRBE-VF), as the project technical monitor.

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I. INTRODUCTION

Due to the current world oil situation, the U.S. Army wishes to develop a capability to utilize multisource mobility fuels. As the sources of these fuels change, the basic properties of the fuels will also change. The Army currently specifies acceptable property limits for its fuels, but future economic and availability considerations may necessitate expansion of these time-proven limits.

Qualitative fuel property effects on engine startability have long been known and have been incorporated into existing specification limits. Expansion of these limits requires quantitative knowledge of these fuel property effects in order to minimize startability problems with Army vehicles. Figure 1 illustrates a methodology for evaluating new/synthetic fuels to assure that there will be no impairment to overall Army mission.(1)* The work described in this report falls under the heading of Full-Scale Multicylinder Engine Performance Testing and provides feedback information to the qualification system.

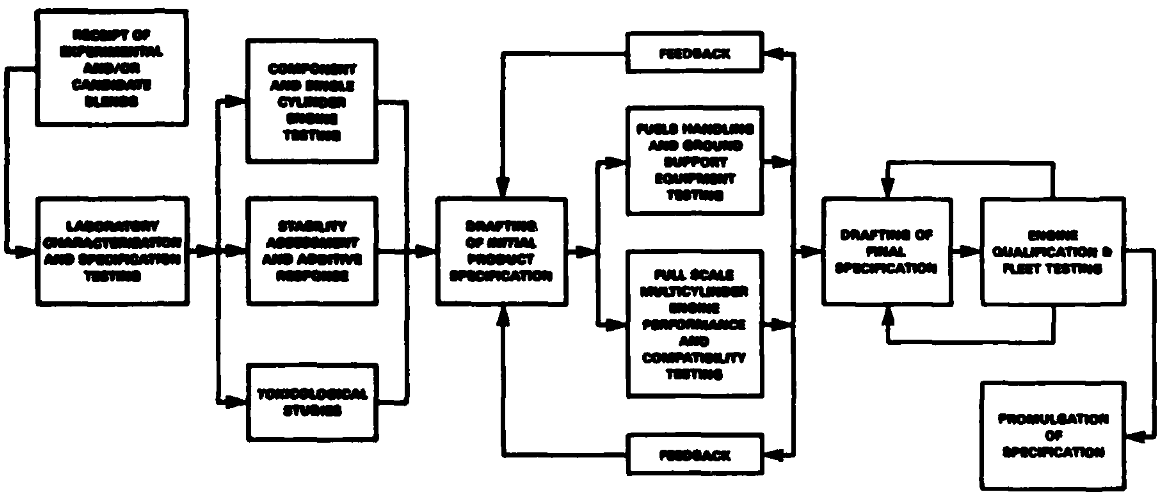

FIGURE 1. PROCESS FOR EVALUATING ALTERNATIVE AND/OR NEW FUELS

* Underscored numbers in parentheses refer to the list of references at the end of this report.

Fuel properties expected to affect low-temperature startability are kinematic viscosity, boiling range, cetane number, autoignition temperature, flash point, and cloud point. Cloud point relates to the ability of the fuel to flow through the screens, hoses, and filters of the fuel system. Viscosity relates to the pumpability of the fuel in both the fuel pump and injection system. Viscosity affects the atomization of the fuel when injected into the combustion chamber. The boiling range of the fuel determines how much of the fuel is vaporized at the temperatures encountered in the combustion chamber under starting conditions. Flash point and autoignition temperature relate to the initiation of combustion in the combustion chamber. Cetane number is a measure of ignition delay and has been determined to play an important role in the starting process.(2-4)

Other parameters affecting startability are engine design, cranking rpm, and ambient temperature. In this study, the cranking rpm was fixed at 150 rpm using a special variable speed cranking system. This speed is used in other studies of low-temperature combustion and is a reasonable minimum low-temperature cranking speed for this engine.(5-7) Ambient temperature was controlled by circulating chilled coolant through the engine, and intake air temperature was controlled with a vortex tube (Hilsch tube).

II. BACKGROUND

Diesel engines ignite fuel by spraying the fuel into high-temperature, high-pressure air and allowing the fuel to autoignite. The high temperatures are generated by isentropic compression of the intake air charge. A variety of factors affects the temperature of the air at the time of fuel injection. These factors include ambient temperature, effective engine compression ratio, cranking speed, duration of cranking time, and injection timing. Properties of the fuel have a negligible effect on these variables.

However, fuel properties do play an important role in the autoignition process. As the fuel is injected into the heated air in the combustion

chamber, the fuel is atomized into droplets of varying sizes and dispersed as plumes of droplets and entrained air. The droplets are then heated by the air and partially evaporated. Also during this period, chemical reactions are occurring, which eventually lead to exothermic oxidation reactions between the fuel components and oxygen. If these reactions liberate sufficient heat quickly enough, the increased temperature further accelerates these combustion processes, and ignition is said to have occurred. Obviously, this ignition process is complex and is not understood in its entirety. However, the total ignition delay period from beginning of injection to ignition (injection, atomization, evaporation, mixing) consists of a physical delay period, and a chemical delay period (chain breaking, radical generation, oxidation) before ignition. This total process is currently quantitized by cetane number.

The cetane number of a fuel is determined by operating a special test engine on the fuel and measuring the engine compression ratio necessary to produce a 13-degree ignition delay at carefully controlled operating conditions.(8,9) Several researchers have shown that the cetane number is a fuel characteristic that correlates strongly with the ease of starting of diesel engines.(2,4)

The cetane number measurement ties together a number of fuel properties. These include viscosity effects on atomization, boiling point distribution which influences evaporization, chemical composition, etc. It has been realized that the peculiarities of the CFR cetane engine may mean that other diesel engines may not respond identically to fuel characteristic variations. Nevertheless, cetane number has been an acceptable indicator of fuel ignition quality for field applications. This was particularly true when diesel fuels were generally uniform in physical properties and the cetane number specification was maintained at a sufficiently high level to provide considerable starting margin under most conditions.

However, with the recent interest in nonhydrocarbon diesel fuels, and non-petroleum hydrocarbons, indications have arisen that the cetane number may not be a totally adequate measure of rapidity of autoignition. This difficulty is further aggravated by a continuing decline in crude oil quality,

making maintenance of high cetane numbers increasingly expensive. For the military, the prospect of operating its diesel equipment on fuels that fail to meet current procurement specifications has placed additional emphasis on developing more detailed knowledge of the engine and fuel factors influencing engine startability.

One objective of this project was to more closely determine the actual fuel characteristics required to ensure startability of the Detroit Diesel 4-53T engine at low temperatures. A second objective was to determine if the design features of this engine—injection system, air motion, heat transfer rates, etc.—have changed the relative importance of fuel properties in determining the total ignition delay. Such changes in the response of this engine, relative to that of the CFR cetane engine, would result in cetane number being an inadequate predictor of minimum starting temperatures.

III. EXPERIMENTAL PROCEDURES AND EQUIPMENT

A. Test Engine and Setup

The Detroit Diesel 4-53T engine was chosen as the test engine due to its relatively high recommended minimum unaided starting temperature, low fuel consumption, small size, and density of the 53 series engines in the Army's fleet. Detroit Diesel recommends the use of starting aids at temperatures less than 4°C (40°F).(10) The engine and a list of specifications are shown in Figure 2 (note that the picture is not from this test program). The engine was insulated with 3 inches of fiberglass batting, and plumbing was installed to circulate chilled coolant through the engine. The circulating coolant was 60 percent by weight ethylene glycol and 40 percent by weight water. The circulating coolant was chilled by passing through a coil immersed in Stoddard solvent and dry ice. Temperatures in the engine were controlled by varying the flow rates of the circulating coolant and controlling the amount of dry ice in the Stoddard solvent tank. Figure 3 depicts the cooling system.

Model: 4-53T (5047-5340)
Engine Type: Two-cycle compression ignition, direct injection, uniflo scavenging, turbosupercharged
Cylinders: 4, inline
Displacement: 3.48 L (212 in.^{3})
Bore: 9.84 cm (3.87 in.)
Stroke: 11.43 cm (4.5 in.)
Compression Ratio: 18.7:1
Fuel Injection: DD 5A60 unit injectors
Rated Power: 127 kW (170 BHP) at 2500 rpm
Rated Torque: 545 N·M (402 lb-ft) at 1800 rpm

FIGURE 2. DETROIT DIESEL 4-53T TEST SETUP AND ENGINE SPECIFICATIONS

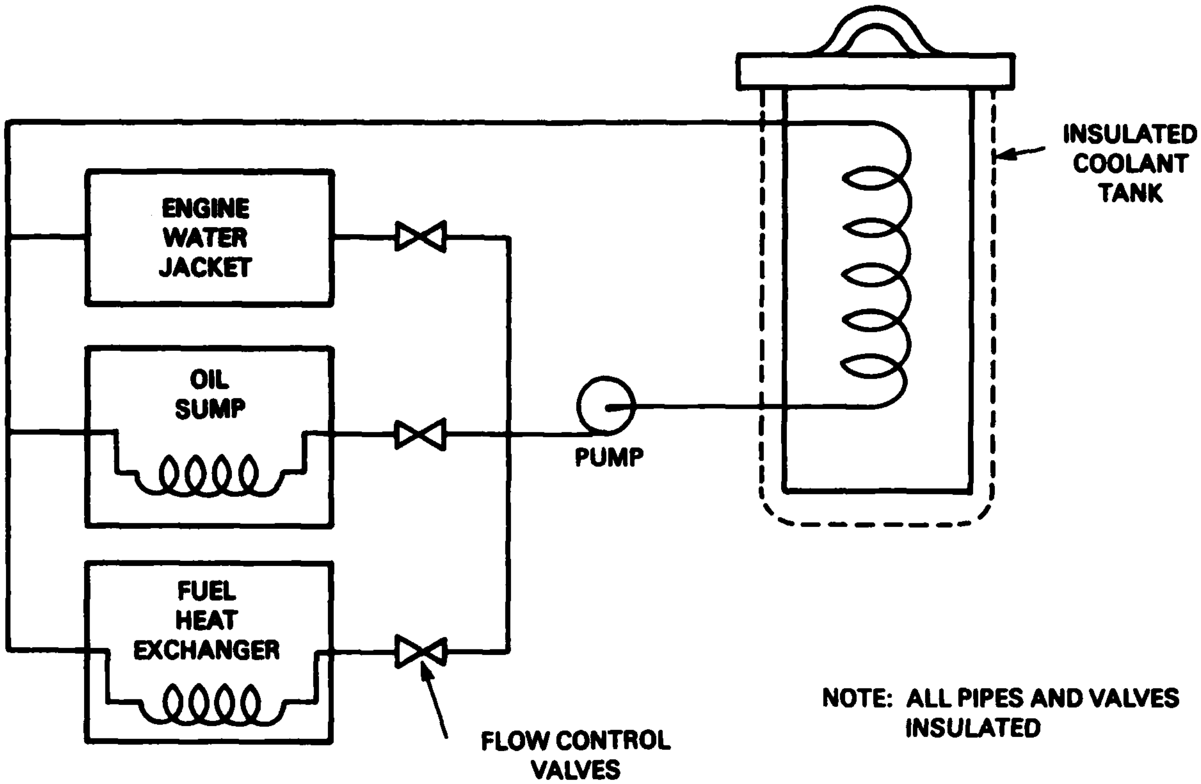

FIGURE 3. COOLING SYSTEM SCHEMATIC

Inlet air temperature was controlled by running dried compressed air through a vortex tube (Hilsch tube). Figure 4 depicts the inlet air system. In practice, cold air was allowed to escape from the inlet air pipe until the engine was cranked. More air was supplied to the inlet air tube than the engine would take in. Excess air vented through the inlet air tube and was observed with a telltale (see Figure 3). No air filter was used for this test.

Engine cranking speed was controlled at 150 rpm with a variable speed external cranking system. The cranking system was equipped with an over-running clutch (sprag clutch) so that the engine could start and come up to idle speed.

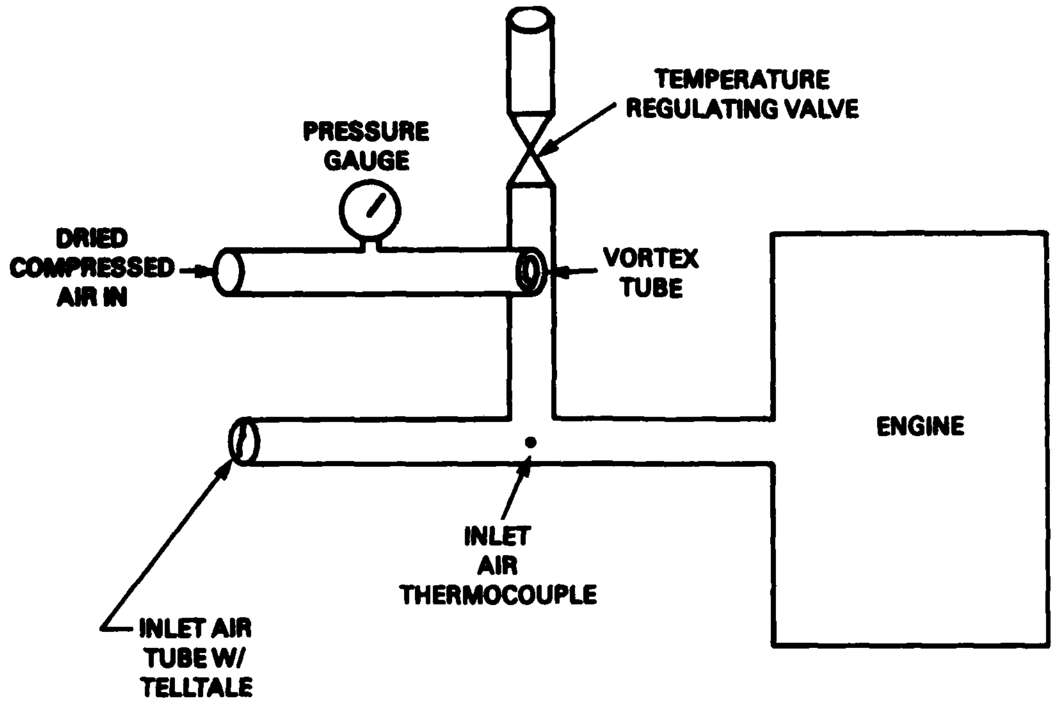

FIGURE 4. INLET AIR SYSTEM SCHEMATIC

The fuel system consisted of the normal engine-mounted lines, filters, and pumps except that the primary fuel filter was removed. Fuel supply was from a 1-gallon reservoir resting on a fuel scale at engine height. Return fuel was routed back to the 1-gallon container. Fuel lines were supported using a laboratory stand such that the fuel weight in the reservoir could be determined before and after the start attempts. The fuel filter and fuel heat exchanger were cooled in order to assure that the test fuel would be at or near the test temperatures. The fuel supply can was not cooled due to the problems of accurately weighing an insulated cooled container. The fuel system schematic is illustrated in Figure 5.

B. Lubricant

The engine lubricant used throughout the test was a qualified MIL-L-46167 Arctic engine oil. This lubricant was chosen as being representative of

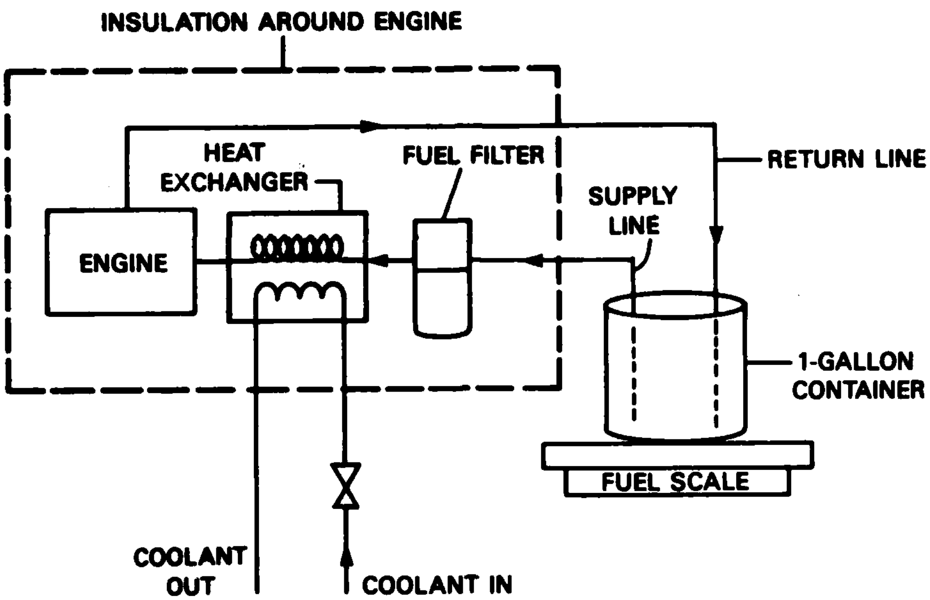

FIGURE 5. FUEL SYSTEM SCHEMATIC

Army field use and providing good low-temperature viscosity and flow characteristics.

C. Test Fuels

Twenty-one hydrocarbon fuels were evaluated in this program. Ten of the fuels were designated neat fuels, meaning that they contained no additional additives nor were blends of different neat fuels. Eleven of the fuels were blends of the neat fuels and several additives.

Summaries of the test fuel descriptions and test fuel properties are shown in Tables 1 and 2, respectively. Neat fuels were Caterpillar 1-H/1-G reference fuel, Jet A, BTX Bottoms*, VV-F-800 grade DF-1, Stoddard solvent, kerosene, MIL-T-5624 grade JP-4, Type 1 referee fuel, Type 2 referee fuel, and gas oil. The Type 1 and Type 2 referee fuels listed in Table 1 are

* BTX bottoms consist of C_9 and higher aromatic compounds and are the end product of a petroleum refining process in which benzene, toluene, and xylene are extracted.

TABLE 1. TEST FUEL DESCRIPTIONS

Test Fuel Code	AL Number	Description
1	11372	Caterpillar 1-H/1-G reference fuel
2	10582	Jet A
3	10716	BTX Bottoms (C_9 and heavier aromatics)
4	9294	VV-F-800 grade DF-1
5	11232	Stoddard solvent
6	11233	Kerosene
7	10583	MIL-T-5624 grade JP-4
8	10849	Gas oil
9	11514	JP-4 + 15 percent PAO
10	11515	Stoddard solvent + 15 percent PAO
11	11516	Jet A + 15 percent PAO
12	11517	DF-1 + 15 percent PAO
13	10999	Type 1 referee fuel
14	11017	Type 2 referee fuel
15	11571	JP-4 + 0.11 percent Amyl nitrate
16	11636	Type 1 referee fuel + 1.1 percent amyl nitrate
17	11637	Type 2 referee fuel + 0.19 percent amyl nitrate
18	11638	Jet A + 3.0 percent BTX bottoms
19	11639	Caterpillar 1-H/1-G + 35.0 percent BTX bottoms
20	11640	DF-1 + 23.0 percent BTX bottoms
21	11641	Gas oil + 22.0 percent BTX bottoms

TABLE 2. TEST FUEL PROPERTIES

Determination	Method	Test Fuel 11372	10582	10716	9294	11232	11233	10583	10849	11514	11515
Kinematic Viscosity at 40°C, cSt	D 445	3.0	1.5	0.75	1.95	1.07	1.56	0.78	7.91	1.12	1.39
Distillation Temperature @ Wt% Off, °C	D 2887										
IBP		125.7	140.6	139.9	184.6	85.5	102.2	21.1	215	24	124.8
10		220.5	179.5	158.2	207.8	105.7	173.7	75.3	285	85.1	151.9
20		239.9	193.4	162.6	215.7	167.4	206.5	93.3	307	101.5	163.3
30		256.9	201.3	165.6	221.8	175.2	219.8	115.8	323.3	125.6	169.8
40		270.8	210	168.5	229.3	182.5	231	136.2	337.2	161.2	174.1
50		282.8	218	170.7	236.9	191.2	236.2	162.6	350.7	191.2	177.8
60		295.7	226.3	175.1	245.2	197.6	239.2	188.3	364.7	214	183.7
70		307.2	234.6	180.9	257.2	204.5	244.4	209.3	379.5	235.2	193.4
80		321.8	244.4	185.3	274.8	214	253.3	226.3	397.9	270.1	207.2
90		343	257.2	189.7	304.8	221.3	258.4	246.7	424.3	481.2	474
EP		405.5	312	218.8	362.5	248.8	284.2	309.1	496.7	572.1	566.5
Distillation Temperature @ Wt% Off, °C	D 86*										
IBP		196.9	178.1	165.5	209.9	142.2	161.4	75.8	265.5	82.5	156.6
5%		226.9	190.4	170.9	217.3	163.4	184.8	87.4	288.5	96.0	164.5
10%		237.8	196.3	172.3	221.5	169.4	197.3	97.0	301.1	105.9	168.7
20%		251.6	202.7	172.2	225.0	176.6	214.1	110.7	316.6	119.9	173.0
30%		261.9	207.6	171.2	228.0	181.8	224.3	126.1	327.9	139.6	175.0
50%		278.2	215.0	168.8	233.4	188.8	232.8	161.9	344.5	188.8	175.8
70%		295.2	225.1	172.9	250.5	196.7	234.9	198.6	365.5	231.0	188.9
80%		304.3	230.0	172.3	264.9	202.7	238.2	214.0	378.1	288.3	238.7
90%		322.5	241.8	175.5	290.1	207.9	241.0	232.5	400.9	452.5	445.3
FBP		351.9	272.5	193.7	328.8	231.1	257.6	267.6	434.6	484.5	477.1
Cetane Number	D 613	50	45	5	57	41	47	35	61	43	49
Autoignition Temperature, °C	E 659	245	250	475	245	255	265	245	235	191	185
Cloud Point, °C	D 2500	-6	-46	-6	-21	<-60	-38	<-60	14	-54	<-60
Flash Point, °C	D 93	77.0	63.6	43.6	82.6	36.0	55	-24.0	135.6	-21.0	43.0
Minimum Unaided Starting Temperature, °C**	AFLRL	-4.0	-1.0	ND***	-8.6	2.8	-9.4	1.0	-9.0***	-4.2	-7.6

* Predicted values using ASTM D 2837 data and a correlation from ASTM STP 577 (13)
** Starting temperatures are the average of two start airbox temperatures and two no-start airbox temperatures that are no more than 2°C apart
***These fuels were not included in the statistical analysis due to fuel flow problems or failure to start at room temperature

TABLE 2. TEST FUEL PROPERTIES (CONT'D)

		11516	11517	10999	11017	11571	11636	11637	11638	11639	11640	11641
Kinematic Viscosity at 40°C, cSt	D 445	2.07	2.57	0.76	3.74	0.82	0.78	3.73	1.46	1.80	1.49	3.76
Distillation Temperature @ Wt% Off, °C	D 2887											
IBP		143.1	189.7	25.7	114.7	30.8	28.3	116	138.1	135.1	147.6	150.6
10		185.2	211.3	85.1	247.4	85.1	84.1	248.6	173.7	161.5	162.9	165.1
20		198.4	217.6	106.2	267.9	101.5	110.5	269.9	188.7	170.1	179.7	187.2
30		207.2	223	133.7	282.2	122.5	137.3	283.5	197.6	189.5	203.8	283.5
40		215.4	232.1	160.5	294	143.1	160	295.5	205.2	231.7	212.8	311.4
50		223.7	238.3	166.2	306.1	169.8	164.3	306.2	212.8	254	218.6	330.1
60		234.4	252	178.5	318	194.9	175.2	316.7	219.4	271.4	227.8	346.6
70		245.9	272.3	194.2	330.6	214	191.7	328.5	228.6	288.6	234.8	362.3
80		265.6	317.2	214.7	344.6	231.4	212.1	341.2	237.1	306.9	251.7	378.7
90		469.6	471.8	236.7	361	250.5	234	357	251	329.3	281.4	401.1
EP		565.8	567.2	300.8	441.6	308.3	297.8	426.3	298.6	392.9	351.8	438.3
Distillation Temperature @ Wt% Off, °C	D 86*											
IBP		182.3	213.8	83.1	208.7	84.9	83.5	209.9	173.9	165.7	169.8	149.8
5%		195.5	220.7	95.3	253.3	97.0	95.1	254.8	184.7	169.3	170.9	173.2
10%		201.5	224.3	107.5	264.2	105.9	108.4	265.7	191.0	177.0	181.2	185.2
20%		208.2	226.9	125.2	277.5	118.4	127.9	279.0	198.4	186.6	196.6	238.1
30%		213.2	229.4	139.1	287.2	133.2	141.6	288.4	203.4	203.6	205.1	270.4
50%		220.6	234.8	164.4	301.0	168.0	162.6	301.1	209.9	250.1	215.6	324.4
70%		240.5	277.7	189.4	317.4	203.5	187.6	315.0	219.0	274.4	229.3	345.8
80%		283.1	322.4	203.9	323.2	218.9	201.3	320.9	223.7	291.3	242.7	361.0
90%		442.6	444.2	224.0	339.5	235.9	221.3	335.6	235.7	310.9	269.3	377.2
FBP		475.5	479.4	262.5	373.7	268.8	259.3	366.1	263.5	344.4	316.1	395.9
Cetane Number	D 613	48	60	28	35	39	40	37	42	39	44	46
Autoignition Temperature, °C	E 659	185	179	202	210	190	190	204	185	190	183	180
Cloud Point, °C	D 2500	-48	-16	<-60	3	-60	-50	0	<-60	-15	-22	10
Flash Point, °C	D 93	64.0	84.0	-21.0	32.0	-22.0	-2.0	37.0	55.0	50.0	60.5	60.5
Minimum Unaided Starting Temperature, °C**	AFLRL	-6.0	-9.8	9.0	12.0	-4.0	4.0	3.5	-9.4	-4.5	-4.5	-12.5***

* Predicted values using ASTM D 2837 data and a correlation from ASTM STP 577 (13)

** Starting temperatures are the average of two start airbox temperatures and two no-start airbox temperatures that are no more than 2°C apart

***These fuels were not included in the statistical analysis due to fuel flow problems or failure to start at room temperature

proposed Army referee fuels. Type 1 referee fuel was blended to exhibit high volatility and low cetane number. Type 2 referee fuel was blended for low volatility, low cetane number, and high viscosity. A polyalphaolefin (PAO) compound (6 cSt at 210°F) was added to four of the neat fuels to increase the viscosity of the fuels.(11) The PAO compound also increased the cetane number of the fuels. Amyl nitrate was added to three of the neat fuels in order to increase their cetane numbers.(12) BTX bottoms were added to four of the neat fuels in order to decrease their cetane numbers.

Viscosity range for the test fuels was 0.78 to 7.91 cSt at 40°C. Ten percent boiling point by D 2887 ranged from 84.1° to 285°C. Cetane numbers for the fuels were 5.0 to 61.0. Autoignition temperatures by E 659 were from 180° to 475°C. Cloud points by D 2500 were from <-60°C up to 14°C. Flash points by D 93 ranged from -22° to 135.6°C. Blending of the additives was done on a volume basis. Test fuels were selected to obtain wide variations in the selected fuel properties.

D. Test Procedure

Dry ice was added to the insulated coolant tank in order to begin the cooling process. The coolant pump was turned on (see Figure 3), circulating the chilled coolant through the engine block, oil sump heat exchanger, and fuel heat exchanger. Temperatures at the airbox, oil sump, and fuel heat exchanger were adjusted to the desired test temperature by adding dry ice to the coolant tank and controlling the flow of coolant with individual flow control valves. Temperature stabilization required approximately 3 hours of dry ice and flow adjustments. After the desired test temperatures were achieved, the vortex tube on the inlet air stream was pressurized and adjusted to the test temperature. A sensor on the inlet air pipe assured that sufficient quantities of cold combustion air were supplied to the engine. Pretest temperatures at the airbox, exhaust manifold, oil sump, water jacket, fuel heat exchanger, and inlet air pipe were recorded. In addition, the weight of fuel in the fuel reservoir was recorded.

The engine was cranked at 150 rpm in the full rack position for a maximum of 1 minute. A finite cranking time was selected to improve reproducibility. With the external cranking system employed, the engine could be motored for long periods and thus reduce the minimum starting temperature. This is because extended cranking would heat the combustion chamber through ring/liner friction and heat transfer from the air charge. This heating would reduce the heat lost from the air during the compression event, raising the air temperature at injection and improving the starting. However, in the field the cranking time is limited by the available battery energy and the time to overheat the cranking motor. The 1-minute continous cranking period was chosen as a compromise of these factors. If the engine started and continued running after 1 minute (or less) of cranking, then this was considered a "start" and the after test information recorded. If the engine failed to start or continue running after 1 minute of cranking, then this was considered a "no-start" condition, and the after test information was recorded. This procedure was repeated at different target temperatures until two "start" and two "no-start" runs were completed that were no more than 2°C apart. The average of the two start and two no-start airbox temperatures was considered to be the minimum unaided starting temperature (MUST) for that fuel. Fuel flushing of the injection system consisted of running 1 gallon of the next test fuel through the engine with the fuel return line routed to a dump can. This was done at room temperature with the engine running under its own power. In all, 21 test fuels were run using this procedure.

IV. DISCUSSION OF RESULTS

Figure 6 graphically depicts the results of the cold starting tests. Three types of results were obtained using this procedure. The first type is demonstrated by test fuel 3(AL-10716) (see Tables 1 and 2) which had an extremely low cetane number of 5. This fuel failed to start in the engine at room temperature (12°C). Failure to start was due to the high-aromatic, low-cetane, high-autoignition nature of the fuel. This fuel was excluded from statistical analysis since no numerical value could be placed on its startability.

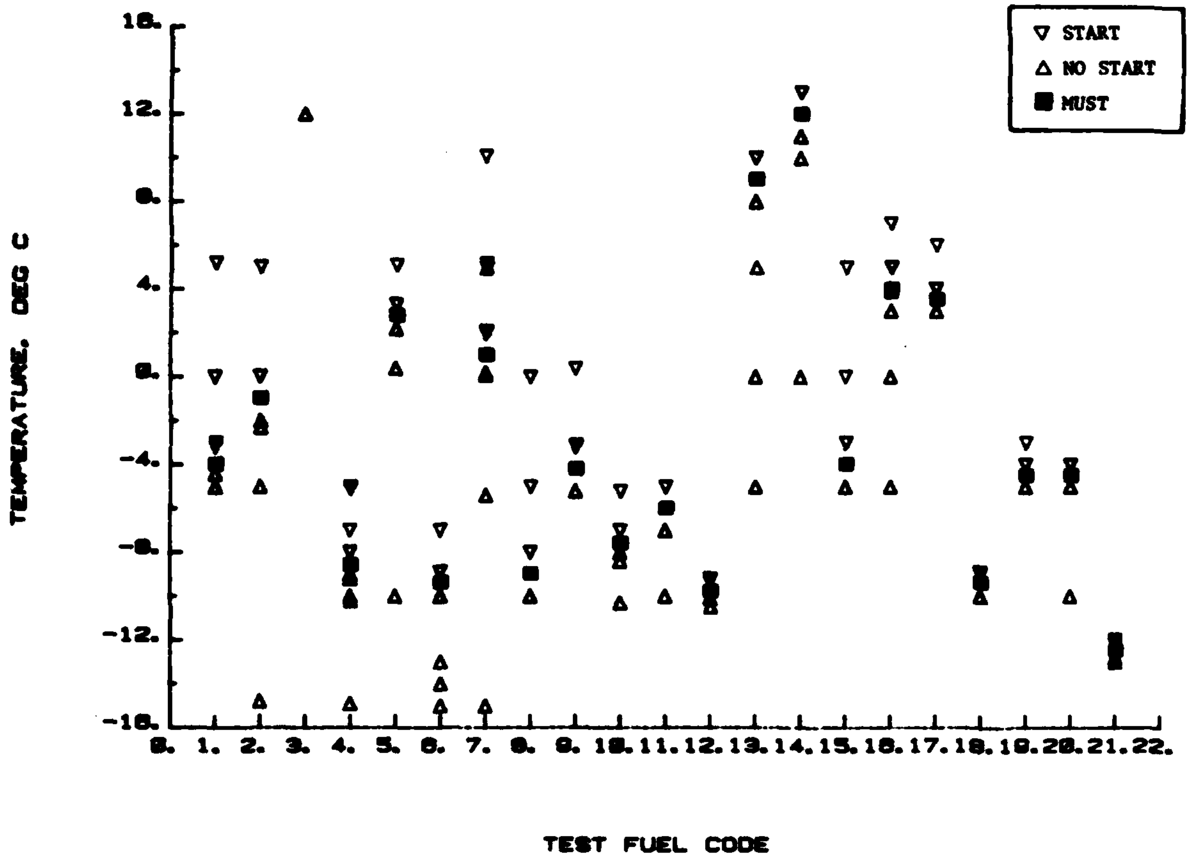

FIGURE 6. STARTING DATA

The second type of result manifested itself in test fuels 8(AL-10849) and 21(AL-11641). These fuels failed to start because of flow-related problems. Starting with these fuels was limited by the cloud points of the fuels. This flow failure was detected by monitoring the before-test fuel reservoir weight and the after-test fuel reservoir weight. No weight change on these fuels indicated that no fuel was consumed (injected) during the start attempt. Since this study was to investigate combustion effects, not pumpability effects, these fuels were not included in the statistical analysis.

The third type of result obtained was the true combustion-related MUST. Eighteen of the test fuels exhibited valid MUST's. MUST's for all the test fuels are shown with fuel properties in Table 2. The SAS (14) stepwise linear regression computer software package was utilized to find the best set of variables to predict MUST. The set of independent variables included viscosity, cetane number, autoignition temperature, flash point, and the boiling point temperature distribution (IBP, 10, 20, 30, 40, 50, 60, 70, 80, 90, EP). Correlations were examined among variables entering the prediction equation through the stepwise regression program. Those variables with high correlation were analyzed, and the appropriate variable was dropped from the set of independent variables. Scatterplots were analyzed for possible variable transformations, and none were found to be necessary.

ASTM D 2887 amd ASTM D 86 boiling point temperatures were used in separate stepwise linear regression analyses. There did not appear to be any advantage of using one method over the other in predicting MUST for this set of data. Although cloud point was determined for each fuel, it was not included in the analysis because of the non-numeric nature of some of the results (e.g., the less than -60°C results). The prediction equation for MUST using the D 2887 boiling point temperature is:

$$\text{MUST} = 32.5445 + 8.6660 * \text{VISCOSITY} - 0.1423 * 50\%\ \text{BOILING POINT} - 0.6968 * \text{CETANE} + 0.0541 * \text{AUTOIGNITION TEMP} \quad (1)$$

The prediction equation for MUST using the D 86 boiling point temperature is:

$$\text{MUST} = 32.8953 + 8.6748 * \text{VISCOSITY} - 0.1459 * 50\%\ \text{BOILING POINT} - 0.6968 * \text{CETANE} + 0.0541 * \text{AUTOIGNITION TEMP} \quad (2)$$

In the equations, MUST is in °C, 50 percent Boiling Point is ASTM D 2887 or ASTM D 86 50 percent off temperature in °C, viscosity is ASTM D 445 kinematic viscosity at 40°C in cSt, autoignition temperature is ASTM E 659 in °C, and cetane is ASTM D 613 cetane number.

Tables 3 and 4 summarize the statistics associated with predicting MUST using the D 2887 and D 86 boiling point temperatures, respectively.

TABLE 3. MULTIPLE LINEAR REGRESSION STATISTICS FOR THE DDA 4-53T ENGINE USING ASTM D 2887 BOILING POINT TEMPERATURES

Engine: DDA 4-53T
Data Points: 18
Multiple R-Square: 0.7811
Standard Error of Estimate: 3.4376

Variable	Coefficient	Standard Error	T	P*
Intercept	32.5445	-	-	-
Viscosity	8.6660	3.0175	2.8720	0.0131
50% BP	-0.1423	0.0621	-2.2920	0.0392
Cetane Number	-0.6968	0.1088	-6.4050	0.0001
Autoignition Temperature	0.0541	0.0298	1.8130	0.0929

* The P value represents the probability that a T statistic would obtain a greater absolute value than the observed given that the true parameter (coefficient) is zero. The T statistic is a method for expressing the significance of a coefficient by its estimated standard error. A P value of 0.10 represents a 10 percent level of significance.

TABLE 4. MULTIPLE LINEAR REGRESSION STATISTICS FOR THE DDA 4-53T ENGINE USING ASTM D 86 BOILING POINT TEMPERATURES

Engine: DDA 4-53T
Data Points: 18
Multiple R-Square: 0.7812
Standard Error of Estimate: 3.4363

Variable	Coefficient	Standard Error	T	P*
Intercept	32.8953	-	-	-
Viscosity	8.6748	3.0176	2.8750	0.0130
50% BP	-0.1459	0.0636	-2.2950	0.0390
Cetane Number	-0.6968	0.1088	-6.4080	0.0001
Autoignition Temperature	0.0541	0.0298	1.8140	0.0928

* The P value represents the probability that a T statistic would obtain a greater absolute value than the observed given that the true parameter (coefficient) is zero. The T statistic is a method for expressing the significance of a coefficient by its estimated standard error. A P value of 0.10 represents a 10 percent level of significance.

Figure 7 is a plot of observed MUST against cetane number for the eighteen test fuels. Obviously, something more than cetane number is affecting the MUST. A regression analysis using cetane number alone to predict MUST yielded an R^2 fit of only 0.599. Using all the fuel properties contained in Equation 1 yields an R^2 fit of 0.7811 as shown in Table 3. Figure 8 plots observed versus predicted values of MUST using Equation 1. The line in Figure 8 represents the predicted equals observed case.

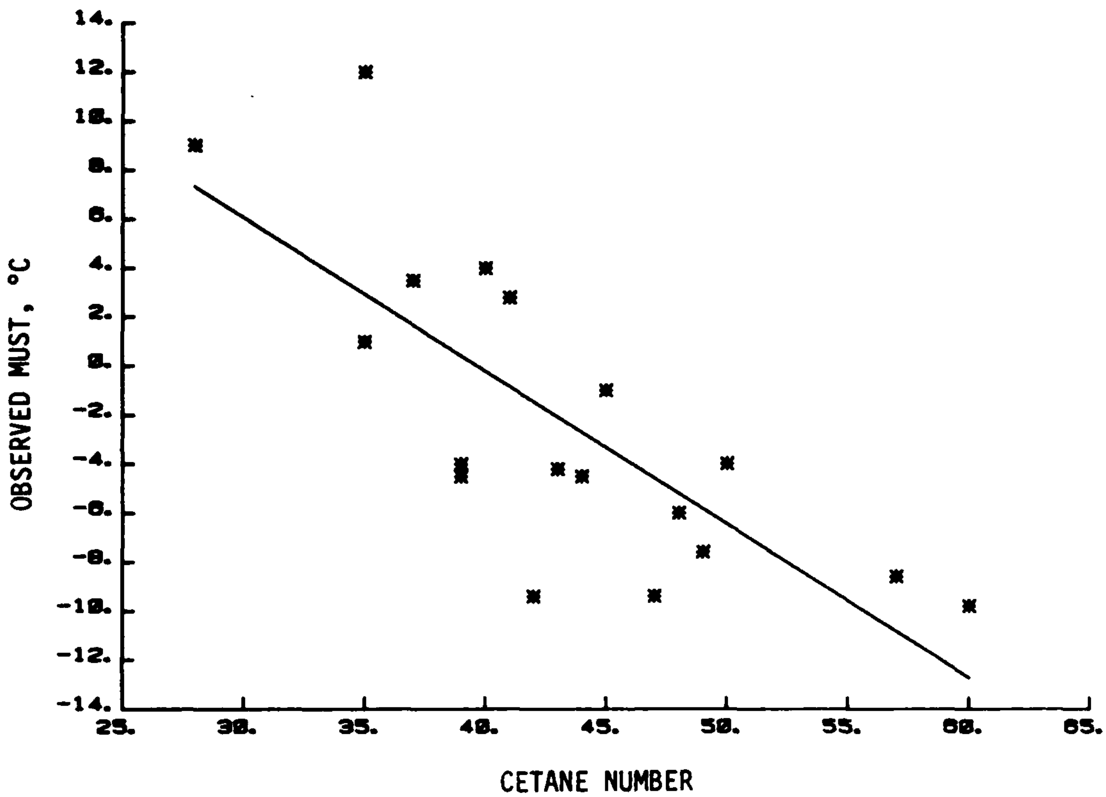

FIGURE 7. OBSERVED MUST VERSUS CETANE NUMBER

V. CONCLUSIONS

- It is possible to quantify the unaided cold-starting characteristics of diesel engines using fuel properties as the independent variables.

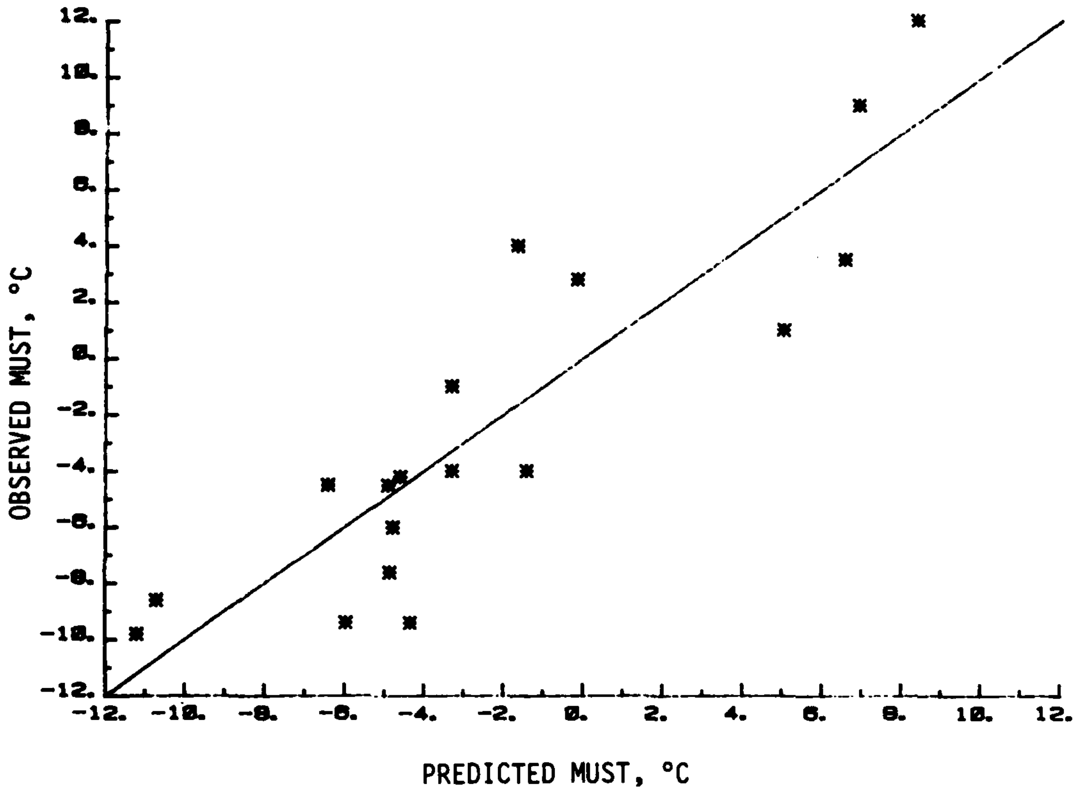

FIGURE 8. OBSERVED MUST VERSUS PREDICTED MUST

- Viscosity, volatility, autoignition temperature, and cetane number are statistically significant ($P < 0.10$) predictors of minimum unaided starting times (MUST's).

- Charts, equations, or computer programs for predicting the MUST's of fuels could be useful for the utilization of off-specification, alternate, or captured fuels in cold climates.

VI. RECOMMENDATIONS

- Future MUST tests should utilize a refrigerated box to obtain cold ambient temperatures. This would afford more uniform, repeatable, and realistic conditions.

- Additional MUST tests should utilize more fuels (to increase the statistical sample size), examine more fuel properties, and utilize different types of diesel engines.

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